

OPTICAL TRACKING SYSTEM AND ASSOCIATED METHODS

Field of the Invention

The invention relates generally to optical tracking systems, and more particularly to optical systems used with a corneal ablation device.

Background of the Invention

The use of lasers to erode all or a portion of a workpiece's surface is known in the art. In the field of ophthalmic medicine, modification of corneal curvature is known to be accomplished using ultraviolet or infrared lasers. The procedure has been referred to as "corneal sculpting."

In such a procedure, application of the treatment laser during unwanted eye movement can degrade the refractive outcome of the surgery. The eye movement or eye positioning is critical since the treatment laser is centered on the patient's theoretical visual axis which, practically speaking, is approximately the center of the patient's pupil. However, this visual axis is difficult to determine due in part to residual eye movement and involuntary eye movement known as saccadic eye movement.

Video-based eye tracking systems automatically recognize and track the position of the eye based upon landmarks present within an image of a human eye. Video-based systems, however, have neither sufficient speed nor accuracy to detect high-speed movement.

Previous disclosure of eye tracking systems and methods has been made in U.S.

Patent Nos. 5,980,513; 6,315,773; and 6,451,008, which are co-owned with the present application, and which are hereby incorporated by reference hereinto. In these patents, an eye treatment laser beam delivery and eye tracking system is provided (FIG. 1). A treatment laser and its projection optics generate laser light along an original beam path (i.e., the optical axis of the system) at an energy level suitable for treating the eye. An optical translator shifts the original beam path in accordance with a specific scanning pattern so that the original beam is shifted onto a resulting beam path that is parallel to the original beam path. An optical angle adjuster changes the resulting beam path's angle relative to the original beam path such that the laser light is incident on the eye.

An eye movement sensor detects measurable amounts of movement of the eye relative to the system's optical axis and then generates error control signals indicative of the movement. The parallel relationship between the eye movement sensor's delivery light path and the treatment laser's resulting beam path is maintained by the optical angle adjuster. In this way, the treatment laser light and the eye movement sensor's light energy are incident on the eye in their parallel relationship.

A portion of the eye movement sensor's light energy is reflected from the eye as reflected energy traveling on a reflected light path back through the optical angle adjuster. The optical receiving arrangement detects the reflected energy and generates the error control signals based on the reflected energy. The optical angle adjuster is responsive to the error control signals to change the treatment laser's resulting beam path and the eye movement sensor's delivery light path in correspondence with one another. In this way, the beam originating from the treatment laser and the light energy originating from the eye movement sensor track along with the eye's movement.

The laser beam delivery and eye tracking system **10** includes treatment laser source **11**, projection optics **12**, X-Y translation mirror optics **13**, beam translation controller **14**, dichroic beamsplitter **15**, and beam angle adjustment mirror optics **16**.

After exiting the projection optics **12**, beam **17** impinges on X-Y translation mirror optics **13**, where beam **17** is translated or shifted independently along each of two orthogonal translation axes as governed by beam translation controller **14**.

The eye tracking portion of system **10** includes eye movement sensor **18**, dichroic beamsplitter **15**, and beam angle adjustment mirror optics **16**. The sensor **18** determines the amount of eye movement and uses same to adjust mirrors **19** and **20** to track along with such eye movement. To do this, sensor **18** first transmits light energy **21**, which has been selected to transmit through dichroic beamsplitter **15**. At the same time, after undergoing beam translation in accordance with the particular treatment procedure, beam **17** impinges on dichroic beamsplitter **15**, which has been selected to reflect beam **17** to the beam angle adjustment mirror optics **16**.

Light energy **21** and beam **17** preferably retain their parallel relationship when they are incident on an eye **23**. Beam angle adjustment mirror optics **16** consists of independently rotating mirrors **19** and **20** under servo control.

Light energy reflected from the eye **23** travels back through optics **16** and beamsplitter **15** for detection at sensor **18**. Sensor **18** determines the amount of eye movement based on the changes in reflection energy **22**. Error control signals indicative of the amount of eye movement are fed back by sensor **18** to beam angle adjustment mirror optics **16**. The error control signals govern the movement or realignment of mirrors

19 and **20** in an effort to drive the error control signals to zero. In doing this, light energy **21** and beam **17** are moved in correspondence with eye movement while the actual position of beam **17** relative to the center of the pupil is controlled by X-Y translation mirror optics **13**.

5 The light energy should preferably lie outside the visible spectrum so as not to interfere or obstruct a surgeon's view of eye **23**, and must be "eye safe" as defined by the American National Standards Institute (ANSI), for example, light energy **21** may be infrared light energy in the 900-nanometer wavelength region.

 Sensor **18** may be broken down into a delivery portion and a receiving portion (FIG. 10 2). Essentially, the delivery portion projects light energy **21** in the form of light spots **24-27** onto a boundary (e.g., iris/pupil boundary **28**) on the surface of eye **23**. The receiving portion monitors light energy **22** in the form of reflections caused by light spots **24-27**.

 In use, spots **24** and **26** are focused and positioned on axis **29**, while spots **25** and **27** are focused and positioned on axis **30** as shown. Axes **29,30** are orthogonal to one another. Spots **24-27** are focused to be incident on and evenly spaced about iris/pupil boundary **28**. The four spots **24-27** are of substantially equal energy and are spaced substantially evenly about and on iris/pupil boundary **28**. This placement provides for two-axis motion sensing as described in the above-referenced co-owned patents.

 This tracking system **10** is effective for eyes dilated to greater than approximately 20 5.5 mm. It would be desirable to be able to track undilated eyes and those that, even dilated, are less than 5.5 mm, or that have an irregular shape.

Summary of the Invention

The present invention is useful for sensing eye position and movement by tracking the position of the eye during surgical procedures, such as, for example, photorefractive keratectomy (PRK), phototherapeutic keratectomy (PTK), and laser in situ keratomileusis (LASIK).

A method of the present invention includes the step of removably affixing a ring member to an eye in surrounding relation to a cornea of the eye. A plurality of incident light spots are transmitted onto the ring member, and reflections are detected from the ring member of the incident light spots. By analyzing the reflections, eye movement can be determined.

A system for tracking eye movement comprises a ring member and means for removably affixing the ring member to an eye in surrounding relation to a cornea of the eye, such as, for example, by applying a vacuum to the ring. Means for transmitting a plurality of incident light spots onto the ring member is provided, as well as means for detecting reflections from the ring member of the incident light spots. Computational means are also provided for determining eye movement from an analysis of the reflections.

This technique may be used on objects other than corneas.

Brief Description of the Drawings

FIG. 1 (prior art) is a block diagram of a laser beam delivery and eye tracking system.

FIG. 2 (prior art) is a block diagram of a prior art eye movement sensor.

FIG. 3 is a side-top perspective view of a vacuum ring connected to a hose.

FIGS. 4A and 4B illustrate two embodiments of the inner face of the ring member.

FIG. 5 is a front view of an eye having the vacuum ring attached thereto with light spots transmitted thereon.

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Detailed Description of the Preferred Embodiments

The present invention will now be described with reference to FIGS. 3-5. A system and method for tracking eye movement comprises a tracking device. The tracking device (FIGS. 3-4B) comprises a ring member **42,42'**. Two embodiments are presented herein, although these are not intended to limit the invention. Both ring members **42,42'** comprise a base **43** affixed to a substantially toroidal ring **44,44'**. The base **43** has a channel **45,45'** therethrough extending from a hose aperture **46** at an outside of the base **43**.

Affixable to the base **43** via the hose aperture **46** is a hose **47**. The hose **47** is in fluid communication with a vacuum source **48**. An inner face **49,49'** of the ring **44,44'** is affixable around a cornea **50** and is retainable in place by means of the vacuum source **48** through the hose **47**. Preferably a center **51,51'** of the ring **44,44'** is affixable to be substantially coincident with a center **52** of the cornea **50**.

In a first embodiment, the ring member **42** (FIG. 4A) comprises a ring **44** that has a toroidal tunnel **53** and a hole **54** from an outside to the tunnel **53**, which is in fluid communication with the base's hose aperture **46** through the channel **45**. A plurality of apertures **56** extend between the tunnel **53** and the inner face **49** of the ring **44**. Vacuum pressure reaches the cornea **50** from the hose **47** through the base channel **45** to the

tunnel **53** and thence to the apertures **56**.

In a second embodiment, the ring member **42'** (FIG. 4B) comprises a ring **44'** that has a substantially toroidal groove **53'** in its inner face **49'**. The groove **53'** is substantially concentric with the ring **44'**. A hole **56'** extends from an outside of the ring **44'** to the groove **53'**. The groove **53'** is in fluid communication with the base's hose aperture **46** through the channel **45'**. Vacuum pressure reaches the cornea **50** from the hose **47** through the base channel **45'** to the groove **53'** and thence to the hole **56'**.

Each ring **44,44'** preferably comprises a color on its outer face **57,57'** that is contrastive with an area of the eye **23** adjacent a location at which the ring member **42,42'** is placed, for improving visibility (FIG. 5). For example, the ring's outer face **57,57'** may comprise an inner ring **58a** that has a light color, such as white, for contrast with the cornea **50**; an outer ring **58b** having a dark color, such as black, provides contrast with the iris **59**.

Tracking using the ring member **42,42'** of the present invention may be achieved in substantially like fashion to that disclosed in the above-referenced '773 patent (FIGS. 1 and 2), wherein a plurality of incident light spots **60-63** are used substantially as the light spots **24-27** of the prior disclosed system **10**. The light spots are transmitted **17** from a light source **64** (FIGS. 2 and 5). Reflections **22** of the light spots **60-63** are detected **18**, and data from these reflections **22** are used to determine and compensate for eye movement using software resident on a processor **64** in signal communication with the detector **18**.

The advantages of the present invention are numerous. Eye movement is measured quantitatively and used to automatically redirect both the laser delivery and eye

tracking portions of the system independent of the laser positioning mechanism. The system operates without interfering with the particular treatment laser or the surgeon performing the eye treatment procedure.

Although the invention has been described relative to specific embodiments thereof,
5 there are numerous variations and modifications that will be readily apparent to those skilled in the art in the light of the above teachings. It is therefore to be understood that, within the scope of the appended claims, the invention may be practiced other than as specifically described.